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Research Paper

P-Y Curves for Single Piles in Sand from the Standard Penetration Test (SPT)

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ABSTRACT

It is nowadays recognized the P-Y curves-based methods are the most commonly used methods for the analysis and design of pile foundations under lateral loads. Such methods have the advantage to account for the non-homogeneity of soil properties and the non-linear pile/soil interface behavior as well.

The paper aims at presenting a practical method to define a hyperbolic function describing the P-Y curves along the pile whose parameters, namely the initial reaction modulus and the limit lateral soil resistance, are correlated with the SPT N-value. The study is based on an extensive interpretation of several full-scale pile loading tests; the test piles being fully instrumented by strain gauges to derive the bending moment profiles along the pile. Finally, the predictive capability of the proposed method was demonstrated by comparing the predicted load-deflection curves by the software SPULL to the experimental ones obtained from lateral loading tests on simply instrumented full-scale piles.

1 Introduction

Pile foundation design under lateral loads is a frequently pile/soil interaction problem in geotechnical practice which is recently based on the ultimate and/or serviceability limit states concepts. Such a modern trend in design demands a displacement-based analysis of the pile/soil system in order to evaluate the pile displacements to satisfy the serviceability limit states requirements as well as the forces induced by the pile displacements to verify the ultimate limit state due to the pile and/or soil failure [1].

The complexity of the pile/soil interaction under lateral loads is mainly due to the tri-dimensional aspect and the multitude of key parameters governing the response of the pile/soil system. Full-scale lateral loading tests present an attractive

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pragmatic approach attempting to overcome the difficulty of rational modelling of this problem but unfortunately eclipsed by the relatively high cost and sometimes by the long time required [2].

The concept of P-Y curves is a practical approach allowing an efficient analysis of the forces and displacements of the pile under horizontal load. These curves are constructed, in many geotechnical codes like API and Eurocode 7, from the mechanical parameters measured from geotechnical tests, in the laboratory or in-situ [3, 4].

The Standard Penetration Test (SPT) has been given an important place in geotechnical projects. This test allows evaluating the density and resistance of cohesionless soils (sands, gravel, silty or clayey sands) by measuring the number of blows Nspt needed to penetrate a steel split barrel sampler to 30 *cm* by dropping a hammer of 63.5 *kg* weight falling down to a height of 0.76 *m*, this procedure being described in the standards ASTM D1586 [5, 6] and ISO 22476-3 [7]. The standard equipment transmits a driving energy equal to 60% of the theoretical free fall energy. Over the past last few decades, the SPT test has gained renewed interest following the evolution towards an international standardization of the equipment. Indeed, the diversity of the devices of the SPT test has systematically resulted in different experimental procedures, significantly influencing the results obtained. The necessity of unifying the language of specialists involved in such a test, a standardized apparatus and test procedure were proposed and subsequently adopted by the ISO 22476-3 standard.

As depicted in Fig. 1a, under horizontal force and/or a bending moment at the head, a current section of the pile at a depth z exhibits a deflection $Y(z)$ due to a forces balance at the pile head and the soil reactions $P(z)$ above the same depth. The relationship between the pile displacement Y and the soil reaction P is commonly described by the so-called P-Y curve which is a constitutive law of the pile/soil interface. The most common law is of the elastic-plastic type (Fig. 1b), characterized by an initial linear portion within the margin of small displacements whose slope is called the initial reaction modulus, and denoted by E_{ti}, and a horizontal asymptote corresponding to large displacements called the lateral soil resistance and denoted Pu [8].

According to Winkler's hypothesis Eq. (1), soil reaction P and pile displacement Y are proportional at a given depth z :

$$P(z) = E_s(z)Y(z) \tag{1}$$

$E_s(z)$ is the lateral reaction modulus at the depth z, whose initial value E_{ti} is defined as the initial slope of the P-Y curve within the small displacements (Fig. 1b). Based on such a hypothesis, the response of the lateral pile can be obtained by solving the bending beam differential equation:

$$E_P I_P \frac{d^4Y(z)}{dz^4} + E_s(z)Y(z) = 0 \tag{2}$$

A simplest form of the solution of this equation is that provided by Hetenyi [9], but only limited to the case of a constant profile of modulus E_s with depth. Alternatively, the finite differences method may be successfully used to solve this equation and LPILE [9] is an example of software based on this technique. Other softwares such as PILATE developed by the IFSTTAR [10], SPULL (Single Pile Under Lateral Loads) developed at the University of Blida [11], are rather based on the technique of discretisation of the pile/soil system into thin slices.

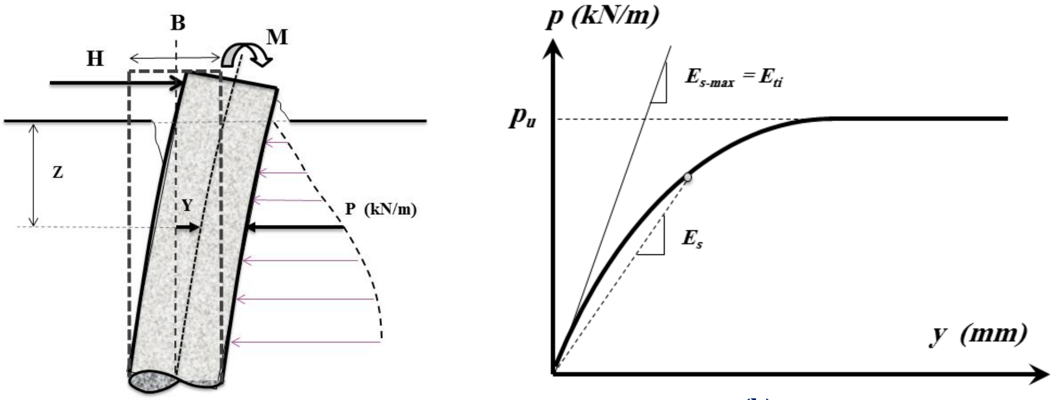
Table 1 – Some recommended values of NH (MN/m3) correlated to the density of sands.

Authors	Relative Density of Sand	Loose	Medium	Dense
Terzaghi [12]	Dry or moist sand	0.95–2.8	3.5–10.9	13.8–27.7
	Submerged sand	0.57–1.7	2.2–7.3	8.7–17.9
Reese et al. [13]	Dry or moist sand	6.8	24.4	61
	Submerged sand	5.4	16.3	34

A practical problem is to determine the lateral reaction modulus for sandy soil, many authors assume a profile of E_s increasing linearly with depth like Terzaghi [12] and Reese et al. [13], and given by Eq. (3). This reaction modulus is correlated to the internal friction angle and the relative density of sand [14].

$$E_s = N_H z \tag{3}$$

N_H is the gradient of the lateral reaction modulus and the table 1 summarizes some usual correlations found in literature.



(a) **(b)**

Fig. 1 – Schemes of forces balance and the P-Y curves.

Christoulas [15] suggested rather a parabolic distribution of reaction modulus formulated as follows:

$$E_s = \beta D^{0.75} N_H z^{0.25} \tag{4}$$

D is the embedded length of the pile, N_H is the gradient of the lateral reaction modulus taking the values recommended by Terzaghi (Table 1), and β is a dimensionless factor taking the values ranging from 0.3 to 0.9.

Finally, it turns out that these experimental correlations are limited to a fairly simple configuration of a homogeneous soil, ignoring the inherent spatial variability of soil properties.

Furthermore, the lateral soil resistance P_u needs to be directly correlated with N_{spt}, which has not yet been published in the literature, to the knowledge of the authors.

Reese et al. [13] suggested a P-Y curve for sands based on the results of back-calculated P-Y curves from loading tests of flexible driven piles embedded in deposit of submerged, dense, fine sand at Mustang Island, based on internal friction angle φ and the sand density. The characteristic backbone curve is composed of 3 straight line segments and a parabolic curve, the initial straight-line portion whose slope is N_H according to equation (3) (Tab.1), final straight-line segment is a horizontal asymptote corresponding to the lateral soil resistance which is the smallest of the two following values [16]:

$$P_{u1} = A\gamma z\left(C_1 z + C_2 B\right) \tag{5}$$

$$P_{u2} = A\gamma z C_3 B \tag{6}$$

C_1, C_2 and C_3 are coefficients of the lateral resistance, as a function of the friction angle of sand.

Reese et al. introduced an experimental calibration factor A to calibrate the lateral soil resistance with respect to the experimental P-Y curves.

O'Neill and Murchison [17] developed another form of P-Y curve for sands based on the above procedure proposed by Reese et al. [13, 18] and using rather a hyperbolic tangent function according to equation (7), which also gives good accuracy compared to the results of the original P-Y curves. This suggestion was adopted by the API (American Petroleum Institute) standard:

$$P\left(Y,z\right)=P_u\,tanh\left(\frac{N_H zY}{P_u}\right) \tag{7}$$

This function has an asymptote corresponding to the lateral soil resistance P_u, identical to that proposed by Reese et al. [13]. The gradient N_H is the slope of the assumed linear profile of the lateral reaction modulus, according to equation (3), and given as a function of the angle of friction.

A is an experimental calibration factor which was simplified using the following linear equation:

$$A=max\left(3-\frac{8z}{10B},0.9\right) \tag{8}$$

Georgiadis et al. [19] proposed another form P-Y curve for sands based on the results of centrifuge tests in medium dense dry sand by using a hyperbolic function. The P-Y curves method involves the estimation of initial reaction modulus E_{ti} having a linear profile versus depth and characterized by a gradient N_H corresponding to the values recommended by Terzaghi (Tab. 1), and a lateral soil resistance recommended by Reese et al. (1974), according to equations (5) and (6).

The depth effect on the P-Y curve was introduced by the depth factor A given by the following equation:

$$A=\left(2-(z/B)/3\geq 1\right) \tag{9}$$

Kubo [20] suggested a P-Y curve for sands, described by the following equation based on the SPT test:

$$P=K_s Bz\sqrt{Y} \tag{10}$$

K_s is the coefficient of the lateral reaction (in MN/m$^{3.5}$), which was correlated to N_{spt} based on the interpretation of full-scale pile loading tests, as follows:

$$K_s=2.52\left(N_0\right)^{0.57} \tag{11}$$

N_0 is the slope of the N_{spt} profile, assumed to be a linear function of depth $\left(N_{spt}=N_0 z\right)$. This form of P-Y curve was adopted by the PHRI (Ports and Harbors Research Institute) standard.

However, a disadvantage of the Kubo's method is that one cannot derive P-Y curves where the profile of N_{spt} is rather heterogeneous (non-linear with depth) [14].

Despite the wealth of worldwide case histories of full-scale lateral load tests of single piles, to the knowledge of the authors, it has not yet been published an original work dealing with a direct derivation of the lateral reaction P-Y curves on the basis of the Standard Penetration Test (SPT) [21].

This paper is aimed at presenting a practical method of construction of the P-Y curves based on a thorough interpretation of some full-scale lateral loading tests on instrumented piles.

The proposed method was validated by predicting the load-displacement response of simply instrumented piles submitted to lateral loading tests in sandy soils. A comparison of the predicted displacements to the measured ones at the pile top showed a very good agreement.

2 Description of the database of pile loading tests

Based on well-documented case studies of full-scale test piles under lateral loading, a database was built from 15 instrumented piles carried out in 9 different sandy sites worldwide [22, 23].

The test piles were made from reinforced or prestressed concrete, steel pipe, H–Pile, micropile or composite materials, and installed into the soil according to many techniques: driving, cast-in-drilled-hole (CIDH), and cast-in-steel-shell (CISS). The range of diameters B, the slenderness ratio D/B and the pile/soil stiffness ratio K_R for the test piles are respectively 0.3–1.2 *m*, 10 – 40, and 1.5×10^{-3} – 2×10^{-1} (Table 2).

Lithology of the experimental sites is mainly composed of multi-layered deposits of silty and/or clayey sand whose N_{spt} profiles are mainly not homogeneous with depth. In some sites, a groundwater table was detected.

During the tests of the fully instrumented piles the strains along the pile were measured at real time allowing to obtain the profiles of the bending moments. Several types of instruments (strain gauges, linear potentiometers, and tiltmeters) were installed on those piles to measure their responses under lateral loading.

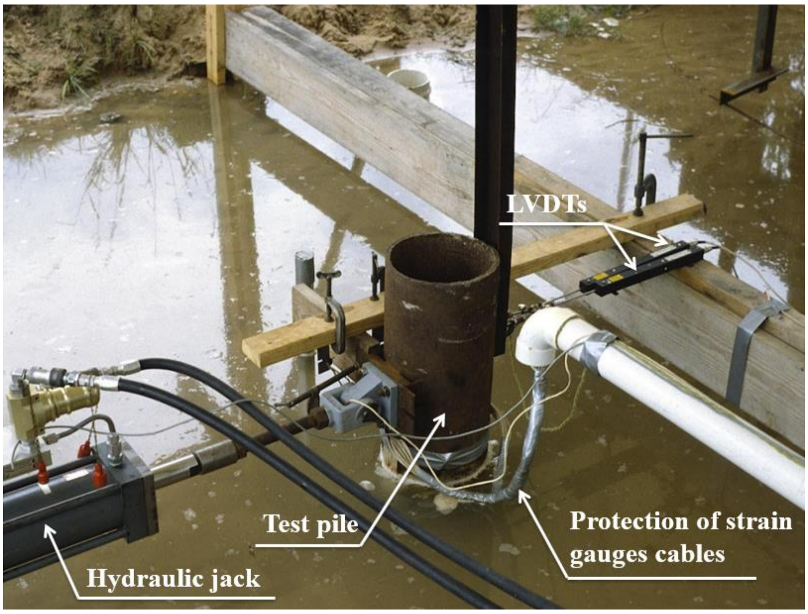


Fig. 2 – Typical lateral load test set-up [24].

3 Methodology of analysis and interpretation of results

The methodology of deriving the P-Y curves using strain gauges from full-scale instrumented lateral loading tests involves three steps [25, 26]:

a. Determining the profiles of moment versus depth based on moment-curvature relationship.
b. Using the double integration technique of the moment versus depth to determine the deflection $Y(z)$ versus depth profiles.
c. Using the double differentiation technique of the profiles of the moment to determine the soil lateral reaction profiles $P(z)$.

The three steps can respectively be described by the following equations [27]:

$$M(z) = \frac{2E_p I_p \varepsilon(z)}{B} \tag{12}$$

Table 2 – Main characteristics of the soil/pile configurations [23]

Site	Location	Soil description	$B(m)$	D/B	E_pI_p (MN.m²)	K_R	GWT (m)	Pile installation	Reference
S_1	California (USA)	Sand (SM- SC)	0.6	20.0	238	0.0113	No.	CIDH (Cast-In-Drilled-Hole)	Juirnarongrit & Ashford [28]
			0.4	11.3	40	0.166			
			1.2	10.0	3530	0.0696			
			1.2	10.0	3530	0.0696			
S_2	Treasure Island (USA)	Sand (SP-SM)	0.32	35.5	28.6	0.00637	0.50	Driven	Ashford & Rollins [29, 30]
			0.3	38.5	37.8	0.00786			
S_3	Treasure Island (USA)	Sand (SP-SM)	0.6	23.0	291.8	0.0118	0.30	CISS (Cast-In-Steel-Shell)	Ashford & Rollins [30, 31]
S_4	Treasure Island (USA)	Sand (SP-SM)	0.9	16.4	1019.4	0.0256	0.10	CISS (Cast-In-Steel-Shell)	Ashford & Rollins [30]
S_5	Taipao (Taiwan)	Multi-layered: Sand (SM)/ Silt (ML)/ Sand (SM)	0.8	40.0	790	0.0027	0.00	Driven	Chiou et al. [27]
S_6	New Zealand	Silty sand	0.45	15.0	110.6	0.138	1.00	Driven	Jennings et al. [32]
			0.45	15.0	110.6	0.189			
S_7	Mustang Island, Texas (USA)	Deep layer of sand	0.61	34.5	168.4	0.0015	0.00	Driven	Reese et al. [13]
S_8	North Carolina (USA)	Multi-layered: Silty Sand / Weathered rock	0.27	20.4	21.13		No.	Driven	Anderson et al. [33-35]
			0.27	20.4	21.13				
S_9	Salt Lake City (USA)	Multi-layered: Clay (CL)/ Silt (ML)/ Clay (CL)/Sand (SM)	0.61	18.4	230		1.07	Driven	Rollins et al. [36]

$$Y(z) = \frac{1}{E_pI_p}\int\left(\int M(z)\,dz\right)dz + Y_0^{'}z + Y_0 \tag{13}$$

$$P(z) = -\frac{d^2M(z)}{dz^2} \tag{14}$$

The Boundary conditions of the equation (13), say $Y_0^{'}$ and Y_0, are respectively the rotation and the pile displacement at the ground surface respectively.

A double integration of the curvature profile versus depth would not induce substantial numerical errors whereas the double differentiation of the moment profile versus depth would result in a non-negligible error, which gives an inaccurate value of P. Therefore, to reduce numerical errors due to the double differentiation, many techniques have been proposed, such as high order global polynomial curve fitting [37], piecewise polynomial curve fitting [38], cubic spline [39], adjusted quintic spline [40], weighted residuals method [41], and smoothed weighted residuals method [42]. However, the main difficulty in this type of analysis is selecting the best fitting method of the bending-moment profiles. In this regard, Bouafia and Garnier [40] suggested a criterion of selection of the fitting function based on the verification of the static equilibrium of the pile under the forces applied at the head of the pile and the lateral soil reaction profile along the pile.

The interpretation of the experimental data for each pile led to the construction of the P-Y reaction curves at various depths according to the methodology described above. Figure 3 illustrates typical experimental P-Y curves of the instrumented pile. It can be seen that P-Y curves do not have a linear shape at different depths and the soil reaction P increases with the depth. Furthermore, beyond a displacement of 4% of B, it can be seen the appearance of a horizontal asymptote of soil reaction. For all the piles, the profile of $E_{ti}(z)$ varies linearly with depth (figure 4), which agrees with the commonly assumed distribution of the reaction modulus along the pile in the cohesionless soils.

The experimental P-Y curves were fitted by a hyperbolic function [1, 2, 8, 22, 25, 26, 40], this formulation is often used to describe the elastoplastic behaviour of the soil as well as the lateral reaction curves. The form of the function is given as follows:

$$P(z) = \frac{Y(z)}{\dfrac{1}{E_{ti}(z)} + \dfrac{|Y(z)|}{P_u(z)}} \tag{15}$$

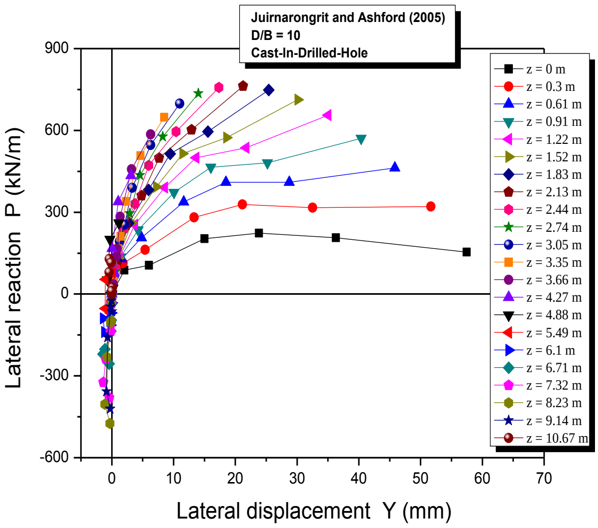


Fig. 3 – Typical experimental P-Y curves

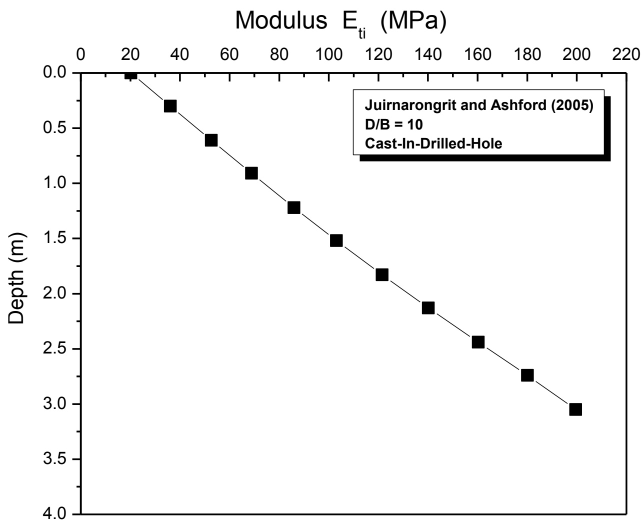


Fig. 4 – Typical lateral reaction modulus profile

At a given depth z, the hyperbolic function can be expressed in terms of the initial lateral reaction modulus E_{ti} and the lateral soil resistance P_u. These two parameters of the P-Y curve can be correlated with the N_{spt} value and the properties of the pile, according to the following general function:

$$f\left(E_{ti}, P_u, N_{spt}, \sigma_v', E_p I_p, B, D\right) = 0 \tag{16}$$

By using the Vashy-Buckingham's theorem of dimensional analysis this equation leads to the dimensionless equation:

$$g\left(\frac{E_{ti}}{N_{spt}\sigma_v'}, \frac{P_u}{B\sigma_v'}, \frac{D}{B}, \frac{E_p I_p}{N_{spt}\sigma_v' D^4}\right) = 0 \tag{17}$$

The first ratio called the modulus number and is denoted K_E such as:

$$E_{ti} = K_E N_{spt} \sigma_v' \tag{18}$$

The second ratio called the lateral resistance factor and is denoted K_N such as:

$$P_u = K_N \sigma_v' B \tag{19}$$

The third and fourth ratios are respectively the pile slenderness ratio and the lateral pile/soil stiffness ratio denoted by K_R and defined by involving a "characteristic soil modulus", noted E_c , such as:

$$K_R = \frac{E_p I_p}{E_c D^4} \tag{20}$$

E_c is defined as the weighted (or analytic) average value along an effective embedded length of the pile D_e as follows:

$$E_c = \frac{1}{D_e} \int_0^{D_e} N_{spt}(z) \sigma_{v0}(z) dz \tag{21}$$

D_e is the effective length of the pile, that is to say, the length of the pile beyond which the pile segments do not deflect. The effective length D_e is defined as the smaller of the two following quantities given by:

$$D_e = \min \left\{ \mathrm{D}, 3\mathrm{L}_0 \right\} \tag{22}$$

L_0 is the elastic length (or the transfer length) defined by:

$$L_0 = \sqrt[4]{\frac{4E_p I_p}{E_{ti}^c}} \tag{23}$$

According to the classical literature of pile foundations, a laterally loaded single piles behaves as a flexible pile if $D > 3L_0$, as a rigid one if $D < L_0/2$, and exhibits an intermediate behaviour if D is ranged between 0.5 and 3 times L_0 .

E_{ti}^c is called the "Characteristic lateral reaction modulus" (or the average lateral reaction modulus) of the "equivalent homogeneous soil" given by:

$$E_{ti}^c = \frac{1}{D_e} \int_0^{D_e} E_{ti}(z) dz \tag{24}$$

On the basis of the result of P-Y curves obtained according to the methodology described above for the instrumented piles, the experimental values of the modulus number K_E and the lateral resistance factor K_N are derived depending on the position of the pile segments with respect to the groundwater table GWT. As an example of the results obtained, figure 5 illustrates the values of the ratio E_{ti}/σ_{v0}' as function of N_{spt} above water table. It can be seen in this figure that all the points may be fitted by a linear function whose slope is K_E . It has been noticed that the values of the factor of lateral resistance K_N very slightly vary with the N_{spt} values which led to a statistical analysis of these values. Figure 6 illustrates typical histograms of the values of the factor of lateral resistance K_N below the water table where the fitting by a Gaussian function led to a mean value of 17. In table 3 are summarized the values of K_E and K_N depending on the position of pile segment with respect to GWT.

Table 3 –Values of KE and KN for flexible piles

Above water table	Below water table
$K_E = 207$	$K_E = 156$
$K_N = 21$	$K_N = 17$

This study concluded that the pile slenderness ratio D/B has negligible effect on the dimensionless parameters K_E and K_N of the P-Y curve. Furthermore, it was found for all the piles studied that the embedded length D is greater than 3 times the elastic length L_0, which implies they behave as flexible piles, which limits the results presented here to the category of flexible piles (that is to say $D > 3L_0$).

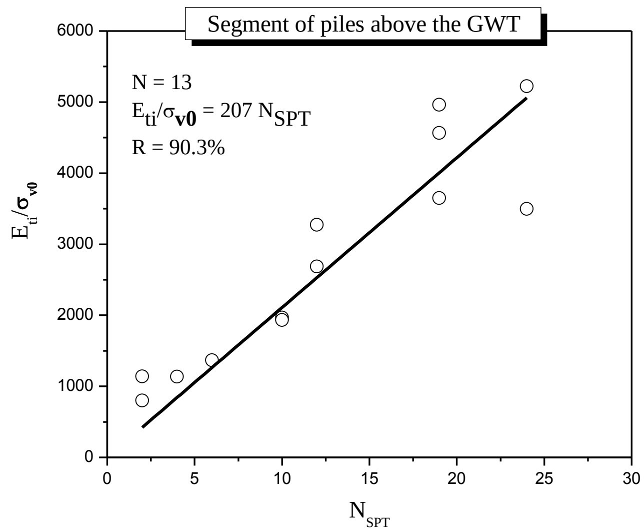


Fig. 5 – Variation of the ratio E_{ti}/σ_{v0}' versus N_{spt}

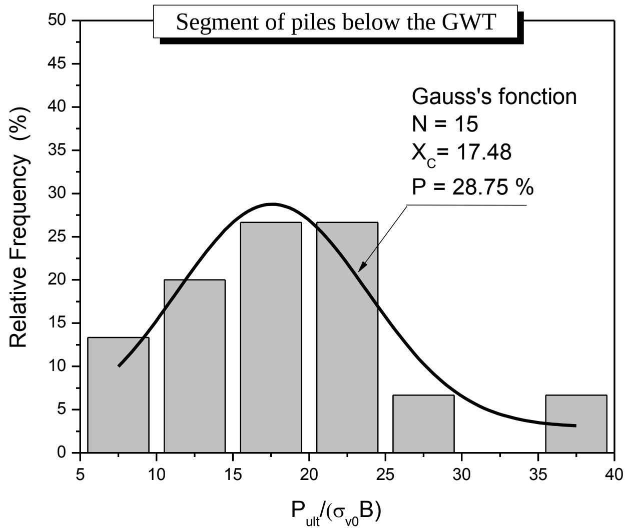


Fig. 6 – The Histogram of values of the lateral resistance factor K_N

Table 3 shows a significant reduction effect of the reaction modulus K_E up to 46% due to the presence of a water table. This fact is in accordance with the values of the reaction modulus shown in in Table 1, where it can be noticed a reduction of 33 – 41% according to Terzaghi, and 21 – 44% according to Reese, which is in good agreement with the value found in this study.

Similarly, the limit lateral resistance of soil exhibits a reduction of about 19% due to the effect of water table level. The theory based on equations (5) and (6) show that the lateral resistance is directly proportional to the vertical overburden stress $\sigma_{v0}\left(z\right)=\gamma z$. Thus, assuming that the internal friction angle of the sand is slightly affected by its degree of saturation, which is a commonly adopted assumption, the coefficients C_1 , C_2 and C_3, depend solely on the friction angle, and therefore will be almost the same below or above the water level. The ratio ${P_{ult}}^{sat}/{P_{ult}}^{dry}$ can then be developed as follows:

$$\frac{{P_{ult}}^{sat}}{{P_{ult}}^{dry}}=\frac{\gamma' z}{\gamma_d z}=\frac{\gamma'}{\gamma_d}=1-\frac{\gamma_w}{\gamma_s}\cong 1-\frac{10}{26.5}=0.62 \tag{25}$$

γ_w and γ_s are the unit weight of water and solid particles respectively. There is a reduction of P_u caused by the presence of the water level equal to 37.8%. This fact confirms the value found in this study.

Finally, it should be noted that in almost all the database studied here, N_{spt} refer to measured values of the blow counts during the SPT test, no mention was made to the commonly used $\left(N_{spt}^1\right)_{60}$ value which corresponds to the normalized and corrected measured values de N_{spt} .

The proposed P-Y curve method described above was validated by direct computation of the experimental piles on the basis of the N_{spt} based P-Y curves by the software SPULL (Single Pile Under Lateral Loads) developed in the university of Blida [43]. The ratio Y_0^{pred}/Y_0^{meas} is represented by a histogram described by a Gaussian distribution function (Figure 7) where an excellent agreement is to be noticed and the mean value of the ratio is almost equal to 1. This fact demonstrates the possibility of a correct description of the behaviour of the test pile, at all load levels, on the basis of this proposed P-Y curve.

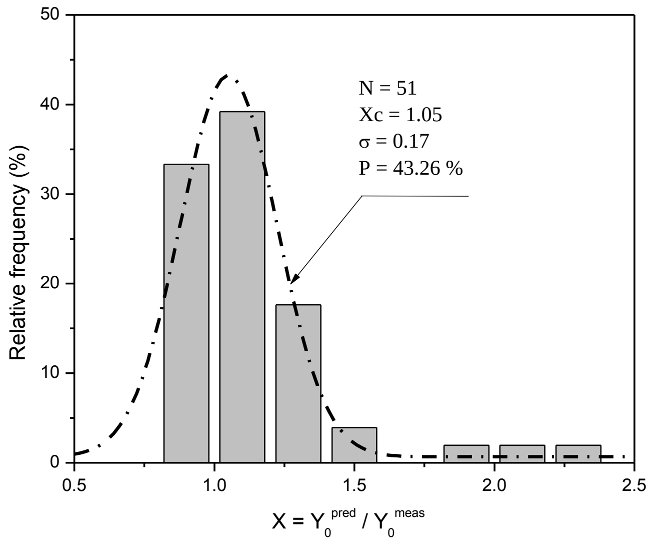


Fig. 7 – Histogram of analysis of the ratio Y_0^{pred} / Y_0^{meas}

4 Methodology of calculation from P-Y curves

Construction of the P-Y curves may be done by following the step-by-step procedure:

1. Along the pile, subdivide the soil into N horizontal slices thin so that the SPT N-values may be considered varying linearly within any slice.
2. Assume the effective embedded length of the pile $D_e = D$
3. Along the pile, compute the characteristic soil modulus E_c defined by equation (21). For practical purposes, the calculation of the integral can be replaced by the summation of the trapezes method.
4. Compute the lateral pile/soil stiffness ratio K_R from the equation (20).
5. Determine the modulus number K_E^i of each layer i, from Table 3, depending on the slice with respect to GWT level.
6. Compute the characteristic initial lateral modulus E_{ti}^c by the following equation:

$$E_{ti}^c = \frac{1}{D_e}\int_0^{D_e} E_{ti}(z)dz = \frac{1}{D_e}\int_0^{D_e} K_E N_{spt}\sigma_{v0}(z)dz \tag{26}$$

7. Compute the elastic length (or the transfer length) L_0 by the equation (23).
8. Compute the effective embedded length D_e of the pile defined by equation (22). If $D > 3L_0$ (flexible pile), then repeat steps 3 to 8 according to an iterative process introducing at each iteration the value of D_e until the convergence.

Otherwise, $D < 3L_0$ the pile is rather non-flexible and the method is not applicable.

9. Construct the P-Y curve by calculating the values of E_{ti} and P_u for each slice along the pile according to equations

(15), (18) and (19) respectively, and table 3.

10. Use software to analyze the single pile under lateral forces on the basis of the suggested P-Y curves like SPULL (Single Pile Under Lateral Loads) developed at the University of Blida [11].

5 External validation of the proposed method

To assess the predictive capability of the proposed method, the lateral load-deflection response of some simply-instrumented piles in sandy soils reported in the literature was predicted. A total of 34 lateral full-scale loading tests carried out in 10 sandy sites were used in this regard [13, 16-19, 27, 29, 31-36, 41, 44-56]. All the piles are characterized by a stiffness ratio K_R less than 10^{-1} and the margin of ratio D/B is 10 – 60, which generally corresponds to flexible piles.

For each test pile, the P-Y curves parameters were defined according to the methodology described above based on the SPT N-value, and a load-deflection curve was simulated by computation using SPULL.

Statistical analysis of the 258 values of the ratio Y_0^{pred}/Y_0^{meas} was undertaken and illustrated by the histogram in figure 8. The ratio predicted deflection to the measured one gave a mean value μ and a standard deviation σ equal respectively to 1.25 and 0.44, with a corresponding probability for this value equal to 43%.

Based on this calculation, it can be concluded that the P-Y method based on the SPT test estimates by a slight excess the pile head deflections, say 25%, which is a rather pessimistic analysis and therefore on the safe side.

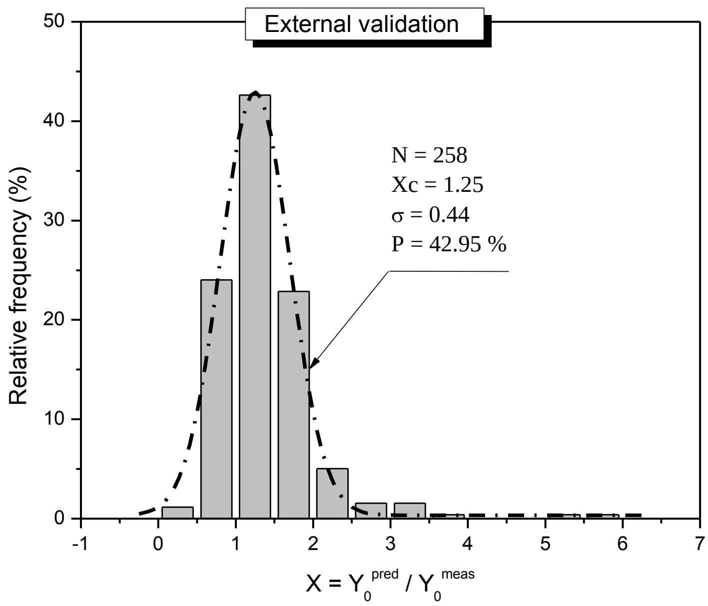


Fig. 8 – Histogram of analysis of the ratio Y_0^{pred}/Y_0^{meas} non instrumented piles

6 Conclusion

This paper presents a practical method defining the parameters of P-Y curves for single piles under lateral loading in sand on the basis of the standard penetration test SPT, by a detailed analysis of several full-scale fully instrumented piles under lateral loading tests carried out in sandy soils. Hyperbolic functions were proposed to describe P-Y curves for such piles.

A synthesis of the results showed that the two parameters of the hyperbolic reaction curve, namely the initial reaction modulus and the lateral soil resistance, were correlated to the N_{spt} value depending on the position of the pile section with respect to the ground water table. The loading test analysis showed the non-influence of the pile slenderness ratio, and also showed that the piles studied are rather flexible ones. The proposed method of construction of P-Y is therefore applicable only for flexible piles.

A methodology of a step-by-step procedure to define the parameters of P-Y curves for a single pile under lateral loads in sandy soils was suggested.

Finally, the proposed method of construction of P-Y curves was validated by predicting the load-deflection response of single laterally loaded piles in sandy soils. The comparison of the predicted pile deflections to the measured ones showed reasonable and rather pessimistic prediction by the proposed method.

REFERENCES

[1]- A. Bouafia, A. Lachenani, Courbes P-Y des pieux isolés dans le sable. Détermination à partir de l'essai pressiométrique. Rev. Fr. Geotech., (108) (2004) 5-15. doi:10.1051/geotech/2004108005

[2]- A. Bouafia. Analysis of PY curves for single piles from the cone penetration test. in In Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering. Alexandria, Egypt (2009), 1103 - 1106. doi:10.3233/978-1-60750-031-5-1103.

[3]- AFNOR, NF P94-262 - Justification of geotechnical work - National application standards for the implementation of Eurocode 7 - Deep foundations Norme française (2012).

[4]- API, ISO19901-4:2003(Modified) - Petroleum and natural gas industries–Specific requirements for offshore structures–Part 4: Geotechnical and foundation design considerations, in 19901-4: 2003 (E). (2014).

[5]- ASTM D1586-11, Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils, ASTM International, West Conshohocken, PA. (2011). doi:10.1520/D1586-11.

[6]- ASTM, D6066-96. Standard Practice for Determining the Normalized Penetration Resistance of Sands for Evaluation of Liquefaction Potential, American Society for Testing and Materials (ASTM) West Conshohocken, PA. (2004).

[7]- ISO 22476-3 - Geotechnical investigation and testing — Field testing — Part 3: Standard penetration test, International Organization for Standardization. International Standards. (2005).

[8]- A. Bouafia, A. Lachenani. Analysis of PY curves for single piles from the prebored pressuremeter test. in Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering. Osaka, Japan: AA Balkema Publishers. (2005), 1955 - 1958. doi:10.3233/978-1-61499-656-9-1955.

[9]- L. Reese, W. Van Impe, Single Piles and Pile Groups Under Lateral Loading. CRC Press, 2011.

[10]- F. Baguelin, R. Frank, Y. Guegan, Calcul sur ordinateur des pieux sollicités horizontalement ou subissant des poussées parasites, in Bulletin de Liaison des Laboratoires des Ponts et Chaussées France. (1976). 113-120.

[11]- A. Laouedj. Pieux sous charges horizontales-Développement d'un programme de calcul et étude comparative des méthodes de calcul à la base des courbes PY. 2011.

[12]- K. Terzaghi, Evalution of Conefficients of Subgrade Reaction. Géotechnique, 5(4) (1955) 297-326. doi:10.1680/geot.1955.5.4.297.

[13]- L.C. Reese, W.R. Cox, F.D. Koop. Analysis of Laterally Loaded Piles in Sand. in Offshore Technology Conference. (1974. doi:10.4043/2080-ms.

[14]- A. Bouafia. Modélisation des pieux chargés latéralement en centrifugeuse. Thèse de doctorat. Université de Nantes -Ecole nationale supérieure de mécanique - Spécialité: génie civil, 1990.

[15]- S. Christoulas, Déplacements de pieux sous charge horizontale, in Bulletin de liaison des Laboratoires des Ponts et Chaussées, Institut Francais des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (1990). 29-37.

[16]- B.J. Meyer, L.C. Reese, Analysis of single piles under lateral loading, University of Texas, Austin. (1979).

[17]- M. O'Neill, J.M. Murchison, An evaluation of py relationships in sands. A report to the American Petroleum Institute, University of Houston, Houston, TX, USA. (1983).

[18]- D.A. Brown, C. Morrison, L.C. Reese, Lateral Load Behavior of Pile Group in Sand. Journal of Geotechnical Engineering, 114(11) (1988) 1261-1276. doi:10.1061/(ASCE)0733-9410(1988)114:11(1261).

[19]- M. Georgiadis, C. Anagnostopoulos, S. Saflekou, Centrifugal testing of laterally loaded piles in sand. Canadian Geotechnical Journal, 29(2) (1992) 208-216. doi:10.1139/t92-024.

[20]- K. Kubo. Experimental study of the behavior of laterally loaded piles. In: Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, Montreal, 1965.

[21]- A. Bouafia. PY curves from the CPT test for laterally loaded single piles in sand. In: Proceedings of The 3rd International Symposium on Cone Penetration Testing (CPT'14) Las Vegas, Nevada, USA, 2014, pp. 881-887.

[22]- A. Bouafia. PY curves from the prebored pressuremeter test for laterally loaded single piles. in Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering. Paris. (2013), 2695-2698.
[23]- A. Laouedj, A. Bouafia. Design and analysis of single piles under lateral loads in cohesionless soils based on the standard penetration test (SPT). in MATEC Web of Conferences. EDP Sciences. (2017), 06001. doi:10.1051/matecconf/201712006001.
[24]- M.A. Pando, Analyses of Lateral Loaded Piles with PY Curves-Observations on the Effect of Pile Flexural Stiffness and Cyclic Loading. NCDOT 7thGeo3T2, Raleigh, NC, Thursday, (2013).
[25]- A. Bouafia. Laterally loaded single piles-Construction of PY curves from the cone penetration test. in 19th International Conference on Soil Mechanics and Geotechnical Engineering. Seoul, Korea. (2017), 2957–2960.
[26]- A. Bouafia, Single piles under horizontal loads in sand: determination of P–Y curves from the prebored pressuremeter test. Geotechnical and Geological Engineering, 25(3) (2007) 283-301. doi:10.1007/s10706-006-9110-7.
[27]- J.-S. Chiou, C.-H. Chen, Y.-C. Chen, Deducing pile responses and soil reactions from inclinometer data of a lateral load test. Soils and Foundations, 48(5) (2008) 609-620. doi:10.3208/sandf.48.609.
[28]- T. Juirnarongrit, S.A. Ashford, Effect of pile diameter on the modulus of sub-grade reaction, in Final Report Submitted to Caltrans under Contract No. 59A0051, Report No. SSRP–2001/22 Department of Structural Engineering, University of California at San Diego, USA, 2005.
[29]- K.M. Rollins, J.D. Lane, T.M. Gerber, Measured and Computed Lateral Response of a Pile Group in Sand. Journal of Geotechnical and Geoenvironmental Engineering, 132(9) (2006) 1241-1241. doi:10.1061/(ASCE)1090-0241(2006)132:9(1241.2).
[30]- S.A. Ashford, K.M. Rollins, TILT : the Treasure Island Liquefaction Test, Report No. SSRP–2001/17, University of California, USA, . (2002).
[31]- K.M. Rollins, T.M. Gerber, J.D. Lane, S.A. Ashford, Lateral Resistance of a Full-Scale Pile Group in Liquefied Sand. Journal of Geotechnical and Geoenvironmental Engineering, 131(1) (2005) 115-125. doi:10.1061/(ASCE)1090-0241(2005)131:1(115).
[32]- D. Jennings, S. Thurston, F. Edmonds. Static and dynamic lateral loading of two piles. in Proceedings of the 8th world conference on earthquake engineering San Francisco, CA. (1985), 561-568.
[33]- J.B. Anderson, F.C. Townsend, B. Grajales, Case History Evaluation of Laterally Loaded Piles. Journal of Geotechnical and Geoenvironmental Engineering, 129(3) (2003) 187-196. doi:10.1061/(ASCE)1090-0241(2003)129:3(187).
[34]- J.B. Anderson, F.C. Townsend, SPT and CPT Testing for Evaluating Lateral Loading of Deep Foundations. Journal of Geotechnical and Geoenvironmental Engineering, 127(11) (2001) 920-925. doi:10.1061/(ASCE)1090-0241(2001)127:11(920).
[35]- J. Brian Anderson, M.R. Babalola, Lateral Load Testing Micropiles to Evaluate the Impact of Threaded Joints and Casing Embedment on Short Micropiles in Shallow Rock. DFI Journal - The Journal of the Deep Foundations Institute, 5(2) (2011) 23-34. doi:10.1179/dfi.2011.009.
[36]- K. Rollins, R. Olsen, J. Egbert, K. Olsen, D. Jensen, B. Garrett, Response, analysis, and design of pile groups subjected to static & dynamic lateral loads, C. Report No. UT-03.03. Brigham Young University. Dept. of, E. Environmental, Editors. (2003).
[37]- L.C. Reese, R.C. Welch, Lateral Loading of Deep Foundations in Stiff Clay. Journal of the Geotechnical Engineering Division, 101(7) (1975) 633-649. doi:10.1061/AJGEB6.0000177.
[38]- H. Matlock, E. Ripperger. Procedures and instrumentation for tests on a laterally loaded pile. in Proceedings, Eighth Texas Conference on Soil Mechanics and Foundation Engineering. Austin, Texas, USA. (1956.
[39]- H. Dou, P.M. Byrne, Dynamic response of single piles and soil–pile interaction. Canadian Geotechnical Journal, 33(1) (1996) 80-96. doi:10.1139/t96-025.
[40]- A. Bouafia. Experimantal study of py curves for piles in sand. in Proc. of the Int. Conference on Centrifuge 91, Bouler Colorado. (1991), 261-268.
[41]- D.W. Wilson. Soil-pile-superstructure interaction in liquefying sand and soft clay. Thèse de doctorat. University of California, Davis., 1998.
[42]- K. Yang, R. Liang, Methods for Deriving p-y Curves from Instrumented Lateral Load Tests. Geotechnical Testing Journal, 30(1) (2007) 31-38. doi:10.1520/GTJ100317.
[43]- A. Laouedj. Apport de l'essai SPT au dimensionnement des pieux isol6s sous charge lat6rale monotone-analyse

expdrimentale et num6rique des courbe de rdaction py. Thèse de doctorat. Université Mouloud Mammeri de Tizi Ouzou, 2018.

[44]- H. Chao-Kuang, L. San-Shyan, C. Shuh-Gi, Lateral Performance of Drilled Shaft Considering Nonlinear Soil and Structure Material Behavior. J. Mar. Sci. Technol., 12(1) (2004) 62-70. doi:10.6119/JMST.200403_12(1).0008.

[45]- D. Mohan, S.P. Shrivastava. Nonlinear Behavior of Single Vertical Pile Under Lateral Loads. in Proceedings of the 3rd Offshore Technology Conference. Dallas, Texas, USA. (1971), 677-686. doi:10.4043/1485-ms.

[46]- L.M. Tucker, J.-L. Briaud, Analysis of the pile load test program at the lock and dam 26 replacement project, Final Report GL-88-11. Texas A and M Univ College Station Dept of Civil Engineering. (1988).

[47]- M.A. Pando, C.D. Ealy, G.M. Filz, J.J. Lesko, E.J. Hoppe, A laboratory and field study of composite piles for bridge substructures, C. Report no. FHWA-HRT-04-043. Virginia Transportation Research, Editor Washington, USA, 2006.

[48]- M.R. Babalola. Evaluation of the lateral response of micropiles via full scale load testing. Thèse de doctorat. The University of North Carolina at Charlotte, 2011.

[49]- P.F. Ruesta, F.C. Townsend, Evaluation of Laterally Loaded Pile Group at Roosevelt Bridge. Journal of Geotechnical and Geoenvironmental Engineering, 123(12) (1997) 1153-1161. doi:10.1061/(ASCE)1090-0241(1997)123:12(1153).

[50]- R.L. Little, J.-L. Briaud, Full scale cyclic lateral load tests on six single piles in sand, Texas A and M Univ College Station Dept of Civil Engineering. (1988).

[51]- S. Fernandez, M. Pando, M. Ashour, Case Study of the Influence of Flexural Stiffness on the Developed Soil Reactions of Three Laterally Loaded Piles, in GeoFlorida 2010. (2010), 1543-1552. doi:10.1061/41095(365)156.

[52]- S.J. Brandenberg, D.W. Wilson, M.M. Rashid, Weighted Residual Numerical Differentiation Algorithm Applied to Experimental Bending Moment Data. Journal of Geotechnical and Geoenvironmental Engineering, 136(6) (2010) 854-863. doi:10.1061/(ASCE)GT.1943-5606.0000277.

[53]- S. Kumar, M. Alizadeh, L. Lalvani, Lateral load-deflection response of single piles in sand. Electronic Journal of Geotechnical Engineering, 5 (2000) 2000-2334.

[54]- S.A. Ashford, T. Juirnarongrit, Evaluation of Pile Diameter Effect on Initial Modulus of Subgrade Reaction. Journal of Geotechnical and Geoenvironmental Engineering, 129(3) (2003) 234-242. doi:10.1061/(ASCE)1090-0241(2003)129:3(234).

[55]- S.S.C. Liao, R.V. Whitman, Overburden Correction Factors for SPT in Sand. Journal of Geotechnical Engineering, 112(3) (1986) 373-377. doi:10.1061/(ASCE)0733-9410(1986)112:3(373).

[56]- T. Juirnarongrit, S.A. Ashford, Lateral Load Behavior of Cast-in-Drilled-Hole Piles in Weakly Cemented Sand. Transportation Research Record, 1868(1) (2004) 190-198. doi:10.3141/1868-20.